THE CALCULATION OF ABSORBED DOSE AND TISSUE TRANSMISSION FACTORS

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Section I. Purpose and Scope

1. Purpose. The purpose of this technical note is to document the source of tissue transmission factors used in the development of nuclear radiation casualty criteria from animal response experiments. A byproduct of achieving this goal is the elimination of the many prevailing misunderstandings and misuses of the radiation related terms and quantities. This technical note has three specific objectives:

a. Define and standardize the radiobiological terminology used by the US Army Nuclear Agency.

b. Describe and document the methodology used by the US Army Nuclear Agency in calculating absorbed doses resulting from exposure to initial nuclear radiation.[1]

c. Calculate and document the tissue transmission factors used by the US Army Nuclear Agency in developing initial nuclear radiation casualty criteria.

2. Scope. This note briefly describes various quantities and terms that are used herein; references to the rigorous definitions are cited. While this note treats the calculations of dose, it does not treat the biochemical implications of dose. Doses arising from exposures to charged particles (alpha, beta, etc.) are not discussed. Calculations of absorbed doses and the development of tissue transmission factors from those calculations are presented.

Section II. Interaction Between Radiation and Tissue

1. General. Ionizing radiation affects matter primarily by a transfer of kinetic energy from the radiation to the matter. This transfer of energy is accomplished by a variety of processes. The process which occurs depends on a number of factors, the most important ones being the type of radiation, the kinetic energies of the radiation involved, and the composition of the matter being traversed. In tissue, the portion of the radiation's kinetic energy which is absorbed by the tissue is eventually absorbed through atomic excitations and ionizations caused by charged particles. These ionizations and excitations break chemical bonds in molecules forming ion-pairs and/or free radicals which may subsequently recombine into different molecules, thus altering the biochemical makeup of cells, membranes, etc. The amount of damage to biological tissue depends primarily on the amount of energy per unit mass of tissue that is absorbed by the tissue rather than on

[1] As discussed in Chapter 2 of FM 101-31-1, only neutron and gamma radiations are of concern; the alpha and beta particles are disregarded.

the incident kinetic energy of the radiation. Reference 1 contains a detailed discussion of radiation effects on biochemical systems.

Three general types of radiation are: charged particles (electrons, protons, alpha particles), electromagnetic radiation (photons), and uncharged or neutral particles (neutrons). The two latter types of radiation are referred to as indirectly ionizing particles (or radiation). In the course of their interactions with matter they give rise to charged particles which are directly ionizing particles. In this note the explicit interactions between these directly ionizing particles and matter are not discussed. The interaction mechanisms for photons and neutrons are discussed in more detail in the following paragraphs.

2. Photons. All photons are electromagnetic radiation. If they originate in nuclear reactions (such as occur in a nuclear detonation), they are called gamma rays. If they originate in atomic transitions (also referred to as electronic transitions), they are called x rays. If they result from the deceleration of charged particles, they are called bremsstrahlung. The properties of all photons depend on their energy, not on their origin. Photons transfer their kinetic energy to matter primarily through three general processes: the photoelectric effect, Compton scattering, and pair production. The probability of any particular interaction or combination of interactions occurring is expressed numerically by an energy dependent quantity known as the cross section.[2]

a. Photoelectric effect. A photon interacts with an atom and transfers all of its kinetic energy to an electron, which is then ejected from its orbit — an ionization.

b. Compton scattering. A higher energy photon interacts with an atom and loses part of its energy to an orbital electron causing an ionization. The less energetic photon continues traveling, usually in a different direction and may interact with another atom.

c. Pair production. A high energy photon (kinetic energy greater than 1.02 MeV) passing close to a heavy nucleus may suddenly disappear with an electron and a positron appearing in its place. The photon's kinetic energy in excess of 1.02 MeV is divided equally and appears as kinetic energy of the electron-positron pair.

3. Neutrons. Neutrons are characterized by their kinetic energy into one of the four groupings shown in Table 1.

[2] A further discussion of cross sections may be found in Reference 2.

Grouping	Approximate Energy Interval
Relativistic	>15 MeV
Fast	100 keV to 15 MeV
Intermediate (epithermal)	0.5 eV to 100 keV
Thermal	<0.5 eV

Table 1 - Neutron Energy Groupings

As is the case for photons, the type of neutron interaction that occurs depends, to a major degree, on the neutron's kinetic energy. There are four principal types of interactions between neutrons and tissue; elastic scattering, inelastic scattering, radiative capture and other nonelastic nuclear interactions. Again, the cross section describes the probabilities of occurrence. Table 2 lists by energy group the most important interaction with tissue, i.e., the interaction that contributes most towards energy transfer to the tissue.

Energy Group	Interaction
Relativistic	Nonelastic Interactions
Fast	Elastic Scattering
Intermediate	Elastic Scattering
Thermal	Radiative Capture

Table 2 - Most Important Interaction with Tissue

A more detailed description of these interactions follows.

a. Elastic scattering. The neutron collides with a nucleus, loses some of its kinetic energy, and continues traveling, usually in a different direction. The energy lost by the neutron appears as kinetic energy of the recoil nucleus; the struck nucleus is not excited to a higher energy state. A larger proportion of a colliding neutron's kinetic energy is transferred to target nuclei of low atomic weight than to target nuclei of high atomic weight. In tissue there is a large abundance of hydrogen present; hence, elastic collisions between neutrons and hydrogen nuclei (protons) is the most effective mechanism for transferring the neutron's kinetic energy to the tissue.[3]

[3] Strictly speaking, this is only true for fast neutrons and intermediate neutrons since for relativistic neutrons and thermal neutrons other mechanisms dominate.

b. Inelastic scattering. A neutron with kinetic energy greater than the inelastic threshold energy (in the range of a few hundred keV) is absorbed into the target nucleus and another neutron of lower energy is emitted leaving the struck nucleus in an excited state. The excited nucleus usually rapidly decays to the ground state by emitting one or more gamma rays.

c. Radiative capture. The neutron is absorbed by the target nucleus forming a compound nucleus which decays by emitting one or more gamma rays (no neutron is emitted). Due to the abundance of hydrogen in tissue, the most prevalent radiative capture reaction is the $^{1}H(n,\gamma)^{2}H$ reaction.[4] This reaction is significant because it releases a 2.2 MeV photon which subsequently contributes to the absorbed dose.

d. Other nonelastic nuclear interactions. The neutron is absorbed by the target nucleus forming a compound nucleus which subsequently emits other particles such as protons, alpha particles, or other heavy particles. For neutron energies greater than 20 MeV, the probability that more than one particle will be emitted becomes significant.

Section III. Radiation Quantities and Units

1. General. The study of radiation effects is continually evolving. As radiation effects have become better understood and as newer concepts have been adopted, the jargon associated with the field has also changed. Unfortunately, while the names of various quantities have been retained, the quantities being described have been redefined so that many original definitions no longer apply. In the following paragraphs, brief descriptions of various radiation quantities and units are presented. These descriptions are current as of this writing, but as has been the case in the past, they may again change in the future. Detailed definitions of all discussed quantities may be found in reference 3.

2. Exposure, X. The exposure is a measure of the number of ionizations in a volume of air produced by photons (ionizations arising from bremsstrahlung emitted by the liberated electrons are specifically excluded). The special unit of exposure is the roentgen (R) and is defined as:

$$1\ R = 2.58 \times 10^{-4}\ \text{Coulombs/kilogram (exactly)}$$

3. Absorbed dose, D. Absorbed dose is a measure of the energy imparted by ionizing radiation to a given mass of matter. The special unit of absorbed dose is the rad and is defined as follows:

$$1\ \text{rad} = 10^{-2}\ \text{Joules/kilogram (exactly)}$$

[4] The notation $^{1}H(n,\gamma)^{2}H$ is a compact way of writing $^{1}H_{1} + {}^{1}n_{0} + {}^{2}H_{1} + \gamma$.

Whenever an absorbed dose is used the material in which the dose was absorbed should be stated explicitly (e.g., rad-tissue, rad-air, rad-silicon). It is also necessary to state explicitly where the dose was absorbed. For example, the dose absorbed by a small volume of tissue at the center of an object is different from the dose absorbed by an identical volume of tissue suspended at the same position but without the object present. This is because any object inserted into a radiation field perturbs that field by absorbing and scattering radiations. As a first approximation to absorbed dose, the object is assumed to not perturb the field and the dose is calculated based on the radiation fluence at the point of interest without the object being present. A dose calculated in this manner is referred to as the free-in-air dose. For small objects such as insects, ion chambers, and dosimeters, the free-in-air dose is adequate; however, for large objects such as a man's body, the attenuations and buildups must be considered, resulting in the so-called depth dose. Another point that should be emphasized is that a man receiving a whole-body absorbed dose of 100 rads absorbs one joule of energy, on the average, in every kilogram of his body.

4. Kerma, K Kerma is the acronym for 'kinetic energy released in materials' and, as is implied, is a measure of the kinetic energy released by photons and neutrons in a given mass of the specified material. Thus, as with absorbed dose, one can have air kerma, tissue kerma, silicon kerma, and others. The special unit of kerma is also the rad. An important distinction is that kerma reflects the energy released in some mass of material while absorbed dose reflects the energy absorbed by that mass of material. The difference between kerma and absorbed dose arises from the fact that energy may be released in one volume element, for example in the form of a proton and not be absorbed in that element, or even anywhere in the object, and hence that released energy may never contribute to the absorbed dose. If charged particle equilibrium[5] exists at the point of interest and bremsstrahlung losses are negligible, then the kerma is equal to the absorbed dose. For most large masses of tissue (e g., men, monkeys, dogs), an effective charged particle equilibrium will exist, except very near the surface where there is a net loss of charged particles to the surroundings. Therefore, when developing nuclear radiation casualty criteria for men, the absorbed dose at internal positions may be approximated by the tissue kerma at the same internal position.

Section IV. Radiation Quality and Dose Equivalent

1. General. Ionizing radiation can induce many physical, chemical, and biological changes. The kind and the extent of change often depend on how the object is exposed to the radiation. As stated in Section II, the foremost dependence is on the amount of energy transferred to the matter from the radiation. However, the type and quality (mass,

[5] Charged particle equilibrium means that the energy carried by charged particles entering the mass element equals the energy leaving it.

charge, energy) of the radiation and the time interval over which the energy is absorbed can exert a profound influence upon the change. The former is demonstrated by the fact that the same dose in rads from different types of radiation does not necessarily produce the same degree of biological effect. The influence of time is demonstrated by the fact that, for a given total dose, the degree of damage to a tissue mass or organ is usually greater when the dose is administered over a brief period of time than when it is delivered over a long period of time or in several increments (dose fractionation). The concept of 'linear energy transfer' is used to describe these features and the concept of 'dose equivalent' is used to account for these features.

2. Linear Energy Transfer (LET). The concept of LET is not explicitly used in this note but is briefly discussed here because the term is widely used in radiobiology. Radiations of different type and quality produce different spatial distributions of energy deposition in tissue and thereby produce different biological responses. The LET is a quantitative measure of the spatial energy deposition and is used to enable one to talk about radiations of different type and quality on an equal basis. The LET of charged particles passing through matter is a measure of the mean energy loss due to collisions per unit distance (track length) traversed by the particle. As a charged particle loses energy while passing through a medium, its LET value will also change, which leads to a distribution in LET over the track length. For indirectly ionizing particles such as neutrons and photons, LETs are determined by a summation of the LETs of the charged particles they produce while passing through matter. The exact mathematical description of LET is the subject of reference 4.

3. Dose equivalent, H. The International Commission on Radiation Units and Measurements (ICRU) recommended that the differences in LET between various radiations be accounted for by the relative biological effectiveness (RBE) in radiobiology applications and by a factor known as the quality factor in radiation protection applications. Definitions of these factors have been extracted from reference 5:

> RBE: Biological potency of one radiation as compared with another. The RBE of radiation A with respect to the reference radiation, B, is defined in terms of the absorbed doses D_A and D_B, which produce equal biological effects. It is equal, therefore, to D_B/D_A. Unless stated otherwise, the reference radiation is assumed to be moderately filtered 200 kVp x radiation.
>
> QUALITY FACTOR: A factor which is used in radiation protection to weight the absorbed dose with regard to its presumed biological effectiveness insofar as it depends on the LET of the charged particles. The quality factor is a function of the LET of the charged particles that deliver the absorbed dose.

The RBEs tend to be experimentally measured quantities for specific effects on tissues or individual organs and as such are tied to the exact experimental conditions used; whereas, the quality factors tend to be analytically developed quantities for specific effects on organisms and are considered limits of the RBE and independent of experimental conditions. Both factors, however, are expressing the same idea: the relative effectiveness of two radiations in producing some biological effect. The ICRU has recommended that the quality factor not be used for exposures leading to absorbed doses greater than about 10 rads. Since RBEs are experimentally measured quantities, however, they may be used when appropriate.

The dose equivalent at the point of interest is defined in reference 3 as:

$$H = DQN,$$

where D is the absorbed dose, Q is the quality factor, and N is the product of any other modifying factors such as those accounting for effects due to dose rate, dose fractionation, and the physical distribution of an internal radioactive source (inhaled or ingested emitters) to name a few. The special unit of dose equivalent is the rem. When D is expressed in rads, H is in rems. For the purpose of developing nuclear radiation casualty criteria for military applications, Q is replaced by RBE in the above expression and N is assumed to be unity.

Section V. History of Dose Calculations

1. General. Doses arising from exposures to ionizing radiations are normally calculated for an incident unit radiation fluence. (Fluence is generally accepted to mean the number of particles which enter a sphere per unit cross-sectional area of that sphere, i.e., the time-integrated particle flux. Reference 6 contains a rigorous generalized formulation of fluence.) The procedure for calculating a dose is to first assume a model for the tissue, generally referred to as the tissue phantom or simply the phantom, and then transport the incident fluence through the phantom accounting for all of the interactions that occur. The validity of the resulting calculated dose depends on the accuracy of the chosen model (i.e., how well the phantom mocks actual tissue composition) and the number of interactions considered.

2. Free-in-air doses. A classic work was performed by Henderson in 1959 (Ref 7) in which he given factors for converting photon flux to absorbed dose rates in air, carbon, and tissue and neutron flux to first collision absorbed dose[6] rates in ethylene and tissue.

[6]Reference 8 contains an excellent discussion of the meanings of "first collision dose."

For calculating the photon conversion factors, Henderson assumed a six element tissue model and considered the three photon interactions discussed in Section II. For calculating the neutron conversion factors, he assumed a four element phantom and considered only elastic scattering; the other neutron interactions were explicitly neglected. Henderson reported his results as first collision absorbed dose rate factors; however, mathematically they are factors for converting unit photon and neutron fluxes to tissue kerma rates free-in-air. (The term kerma had not been developed at that time.) Changing from kerma rate factors to kerma factors results in a quantity which is now referred to as the Henderson Tissue Dose (HTD); however, this quantity is really a tissue kerma free-in-air. In 1967, Auxier and Snyder (Ref 9) improved the neutron kerma calculations by including more of the neutron interactions. Ritts, et. al., (Ref 10) employed an eleven element phantom to calculate the most recent set of fluence-to-kerma factors for monoenergetic gamma rays and neutrons. These kerma factors, when multiplied by the incident fluence, yield the free-in-air kerma.

3. Depth doses. The casualty criteria for personnel exposed to initial nuclear radiation are developed from an extrapolation of the responses of animals exposed to ionizing radiation. Since the radiation induced degradation in performance appears to be a central nervous system effect and also since no specific region of the brain has been identified as the affected area, the absorbed dose at the midhead position (geometric center) has been selected as a more meaningful quantity for use in extrapolation between species than the free-in-air dose. The assumption currently used by the US Army Nuclear Agency is that equal supralethal midhead doses of radiation elicit the same performance degradation in monkeys and men, hence the interest in calculating midhead doses. A midhead dose is properly called a depth dose since the term depth dose refers to the absorbed dose at a point some depth into a finite sample. Prêtre (Ref 11) has pointed out that when calculating depth dose, the simplifying assumption made by Henderson by calculating first collision dose is no longer valid, mostly because it neglects the contribution to the dose from the $^{1}H(n,\gamma)^{2}H$ reaction. The term multicollision dose[7] has recently been adopted, and for the case of neutron irradiation may also include the dose due to gamma rays produced by the neutrons while traversing the matter. The results of calculations of depth doses are usually presented by energy group as unit incident fluence-to-dose conversion factors for various depths into the phantom used. Sometimes, these dose factors are displayed graphically which eliminates the problem of interpolating between tabulated depths.

The calculations of depth doses involve more variables than do those for free-in-air doses. Auxier and Snyder (Ref 13) have shown that the depth dose depends upon the geometry of the phantom, e.g., more scattering occurs in 30 cm thick infinite slabs than in 30 cm diameter cylinders. Snyder and Jones (Ref 14) demonstrated that the angle of incidence of the radiation also affects the depth

[7] Reference 12, page 38.

dose, e.g., the surface dose to a cylindrical phanton irradiated by a slant beam of neutrons may be significantly higher than for a normal beam, and vice versa at the phantom's midpoint. These two effects were discussed in detail by Snyder and Jones at the First Symposium on Neutron Dosimetry in Biology and Medicine held in Munich in May 1972 (Ref 15). Some insight gained by an examination of these effects is that for calculating the depth dose, the radiation source geometry and orientation (whether a normal broad beam, slant broad beam, or an isotropic source), and the phantom geometry (whether a slab, right circular cylinder, right elliptical cylinder, or some combination of these) must be carefully selected to obtain meaningful results. For example, for calculating the mid-head dose received by monkeys irradiated at the AFRRI TRIGA facility, a right circular cylindrical phantom of 3 cm radius exposed to a normal broad beam is appropriate, while for calculating the mid-head dose received by men irradiated downrange from a nuclear detonation, a right elliptical cylindrical phantom of 10 cm and 7 cm semi-major and minor axes exposed to an isotropic radiation source is appropriate.[8]

Section VI. Tissue Transmission Factors

1. General. The tissue transmission factor (TF) expresses the ratio between the depth dose at a specified position and the free-in-air dose at that position. A tissue transmission factor is a function of the quality of the incident radiation, the physical makeup of the tissue, the geometry of the tissue mass, and the depth of interest into the tissue; it is <u>not</u> usually considered a function of the relative amounts of differing types of radiation which comprise the incident radiation field, e.g., the incident neutron-to-gamma ratio.

The term 'neutron dose' refers to the absorbed dose arising from the interactions between incident neutrons and tissue less the dose due to photons released by any of these interactions, e.g., inelastic scattering and radiative capture. The term 'gamma dose' refers to the absorbed dose arising from the interactions between incident photons and tissue plus the dose due to photons originating in neutron interactions with the tissue. Since dosimeters do not distinguish between attenuated photons originally from the incident radiation field and those that originated in the tissue itself, defining the neutron and gamma doses in this manner allows a direct correlation between calculated and measured results.

In general, the more neutrons there are present in an incident radiation field, the more photons there will be present inside the tissue; thus the measured gamma transmission factor for a mixed neutron-gamma radiation field will be greater than if the field consisted solely

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[8] W.S. Snyder and T.D. Jones, ORNL, Private Communication, unpublished.

of photons -- and, in fact, the value can even be greater than unity. For these reasons, in mixed neutron-gamma radiation fields it is convenient to consider the gamma transission factor to be a function of the incident neutron-to-gamma ratio and the energy spectrum of the incident neutrons as well.

The following paragraphs describe the methodology developed and used by the US Army Nuclear Agency to calculate the radiation transmission factors applicable for monkeys exposed to reactor spectrum radiation beams and men exposed to weapon spectrum radiation fields. Such transmission factors allow a more realistic extrapolation from observed monkey responses to expected human responses. The methods described are not intended to be derivations, rather they express empirical relationships between depth doses and free-field doses resulting from exposure to mixed neutron-gamma radiations.

2. Tissue transmission factors for monkeys. For the purpose of this note, it is necessary to determine the neutron and gamma radiation transmission factors to the midhead position for monkeys (specifically male Macaca Mulatta). The monkeys are exposed with their backs towards fairly uniform, broad beams of mixed neutron-gamma radiation at TRIGA reactor facilities. They have an average back-to-front head diameter of 6 cm. As noted in Section V, an appropriate phantom/source combination would be a 3-cm radius right circular cylinder exposed to a normal broad beam. Since depth dose results are not currently available for such a phantom, a larger phantom must be used and adapted to the requirements. The phantom described in reference 5 was chosen and the depth doses at a 3-cm depth were used. (Figures 1 and 2 depict the phantom geometry.) One uncertainty attendant with this approach arises from calculating the dose for a symmetric point, i.e., the midhead position, from the dose at an asymmetric position, i.e., in a mass of tissue that is off of the phantom's midline.

a. Neutrons. While there have been a number of measurements of neutron depth doses in monkey cadavers and phantoms, they do not agree well among themselves. For example, measurements by AFRRI (Ref 16) show a large variance in the neutron transmission factor with changes in the incident neutron-to-gamma ratios. For these reasons, the results of calculations are deemed preferable to those measured transmission factors. A simplifying approximation made in this calculation of transmission factors is the use of monoenergetic incident neutrons; specifically 1 MeV neutrons. According to Figure 15 of reference 5, the neutron dose 3 centimeters into the phantom resulting from exposure to a normal, incident fluence of 1 n/cm^2 of 1 MeV neutrons is 1.98×10^{-9} rad. The free-in-air neutron fluence-to-kerma conversion factor yields the free-in-air dose and for 1 MeV neutrons this factor is 2.43×10^{-9} $rad/(n/cm^2)$. Thus, the neutron transmission factor is given by:

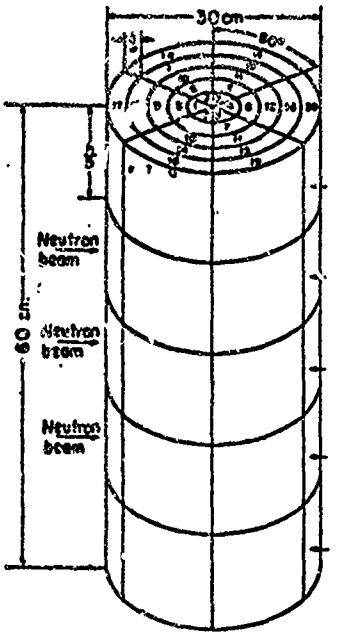

Figure 1 - The cylindrical phantom used in the Monte Carlo dose calculations (Ref 5)

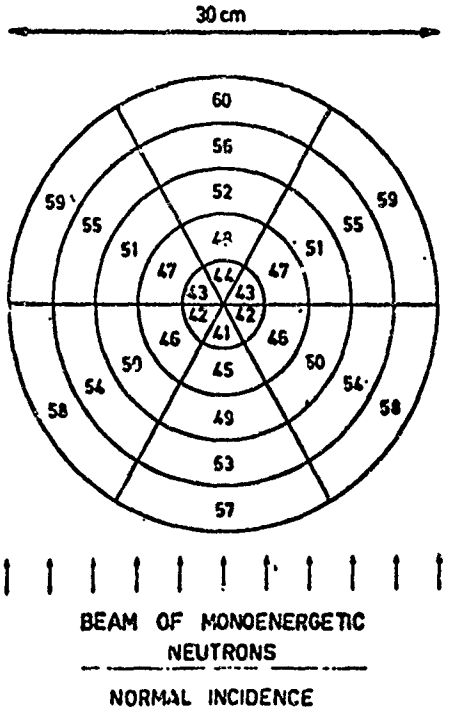

Figure 2 - The central slab of the cylindrical phantom with its 30 volume elements depicted (Ref 5)

$$TF_n = \frac{1.98 \times 10^{-9}}{2.43 \times 10^{-9}} = 0.81$$

b. Photons. There are no depth dose curves currently available for photons incident upon a homogeneous cylindrical phantom of the type used for the neutron dose calculations, but there have been accurate measurements of the transmission factor to the midhead position of a monkey exposed to Cobalt-60 gamma rays (1.17 and 1.33 MeV). AFRRI reported (Ref 16) that transmission factor as 0.92. These measurements were used because the two gamma rays from Cobalt-60 reasonably approximate the TRIGA gamma-ray energy spectrum used in the actual animal experiments. However, to completely determine the gamma transmission factor for exposure to mixed neutron-gamma radiation fields, the neutrons' contributions to the gamma dose must be explicitly included. The following symbols will be used in the development of that explicit relationship:

f_e = Free-in-air neutron-to-gamma dose (in rads) ratio.

D_{ne}, D_{ge} = Free-in-air neutron and gamma doses in rads, respectively.

D_{ni}, D_{gi} = Neutron and gamma doses in rads at the midhead position, respectively.

d_g, d_n = Components of D_{gi} in rads due to incident photons and incident neutrons, respectively.

The definitions of the neutron and gamma tissue transmission factors are:

$$TF_n = \frac{D_{ni}}{D_{ne}} \quad \text{and} \quad TF_g = \frac{D_{gi}}{D_{ge}}$$

Substituting the relation $D_{gi} = d_g + d_n$ into the defining equation for TF_g gives the expression:

$$TF_g = \frac{d_g + d_n}{D_{ge}}$$

Seeking a relation expressing d_n in terms of f_e a quantity k, similar to a buildup factor, is defined such that:

$$d_n = k\, D_{ne}$$

Now the expression for TF_g can be written as:

$$TF_g = \frac{d_g + kD_{ne}}{D_{ge}}$$

However, by definition, the quantity D_{ne}/D_{ge} equals f_e. Thus:

$$TF_g = \frac{d_g}{D_{ge}} + kf_e$$

As previously mentioned, the value for d_g/D_{ge} has been reported as 0.92, corresponding to Cobalt-60 gamma-ray dose measurements. According to Figure 15 of reference 5, the dose due to photons produced by the neutron interactions is 3×10^{-10} rads/(n/cm^2). Dividing by the free-in-air neutron kerma factor results in the quantity k for incident 1 MeV neutrons:

$$k = \frac{3.0 \times 10^{-10}}{2.43 \times 10^{-9}} = 0.12$$

Thus, the gamma transmission factor for monkeys is given by:

$$TF_g = 0.92 + 0.12f_e$$

3. Tissue transmission factors for men. An unshielded man standing at the distances of interest from a nuclear detonation will be exposed to a nearly isotropic initial radiation source. (The radiation source is nearly isotropic because the many scatterings of the neutrons and photons with the air molecules and with the ground result in the radiation striking the man from all directions.) Since the radiation field is nearly isotropic, regardless of a man's orientation to the burst point it is appropriate to use the minimum head dimension when determining the depth doses. A man's head is generally approximated by a right elliptical cylinder with major and minor axes of 20 cm and 14 cm. Using a right circular cylinder of 7 cm radius would be a reasonable approximation. Since no depth dose calculations for that specific phantom are available, a close approximation can be achieved by using a 6 cm radius phantom. Reference 17 presents the results of depth dose calculations in such a phantom isotropically exposed to an equilibrated energy-spectrum neutron-photon source equivalent to that of Hiroshima/Nagasaki type detonations.[9] Thus, the dependence of the components of the depth dose on the energies of the incident radiation has been implicitly considered.

[9] After about 3 mean-free interaction path lengths (approximately 900m slant range in air), the energy spectrum reaches an equilibrium following rapid initial variations with distance. This was originally reported by E.A. Straker in ORNL 4464.

a. Neutrons. From the data reported in reference 17, the neutron dose expected at the midhead position of a man exposed to the radiation from an isotropic equilibrated fission weapon spectrum is 1.17×10^{-9} rads/(n/cm^2). The free-in-air kerma factor appropriate for this energy spectral distribution is listed in reference 17 as 2.3×10^{-9} rads/(n/cm^2); thus, the neutron transmission factor is:

$$TF_n = \frac{1.17 \times 10^{-9}}{2.3 \times 10^{-9}} = 0.51$$

b. Photons. From the data in reference 17, the expected component of the gamma dose at the midhead position of a man exposed to isotropic incident photons from an equilibrated fission weapon spectrum is 2.44×10^{-10} rads/(γ/cm^2). The free-in-air kerma factor appropriate for this energy spectral distribution is listed in reference 17 as 4.54×10^{-10} rads/(γ/cm^2). Thus, the quantity d_g/D_{ge} is

$$\frac{d_g}{D_{ge}} = \frac{2.44 \times 10^{-10}}{4.54 \times 10^{-10}} = 0.54$$

From data in the same reference, the component of the gamma dose due to incident neutrons is 1.13×10^{-10} rads/(n/cm^2). Dividing by the free-in-air neutron kerma factor gives the result:

$$k = \frac{1.13 \times 10^{-10}}{2.3 \times 10^{-9}} = 0.05$$

Hence, for men, the gamma transmission factor is:

$$TF_g = 0.54 + 0.05\ f_e$$

Section VII. Results and Limitations

1. Summary of results. The set of tissue transmission factors used by the US Army Nuclear Agency to determine nuclear radiation casualty criteria is as follows:

	TF_n	TF_g
Monkeys	0.81	$0.92 + 0.12\ f_e$
Men	0.51	$0.54 + 0.05\ f_e$

2. Limitations. The calculations in paragraph 2a of Section VI were for idealized monoenergetic neutrons normally incident on phantoms. How well the monoenergetic simplification represents reality is not quantitatively known. Calculations in the manner of paragraph 2a were performed for men exposed to monoenergetic beams of neutrons and photons and agree quite favorably with measurements in the Alderson Man phantom performed at AFRRI. Those calculations were not presented in this note since a broad monoenergetic beam radiation environment does not describe the typical field environment well at all. They are mentioned only to indicate that the procedure used gives realistic results. Other physical realities tend to limit the general usefulness of any set of transmission factors; among these is the fact that the neutron-to-gamma ratios vary with range, weapon type, and yield. Transmission through shields such as tank armor, foxholes, vehicles, and fortifications perturbs and changes the character of the radiations even more.

The above arguments notwithstanding, the results presented in this section are considered applicable to the development of nuclear radiation casualty criteria, and, in fact, the errors introduced by these approximations may well be second order to the uncertainties in the extrapolation of animal response to human response. However, the search for better and more representative transmission factors will be continued. For example, should future experimentation show that the areas of the brain being affected lie close to the skull, new transmission factors would have to be calculated reflecting the different depths of interest.

APPENDIX A - REFERENCES

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